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(54) **RESONANT DC-DC CONVERTER**

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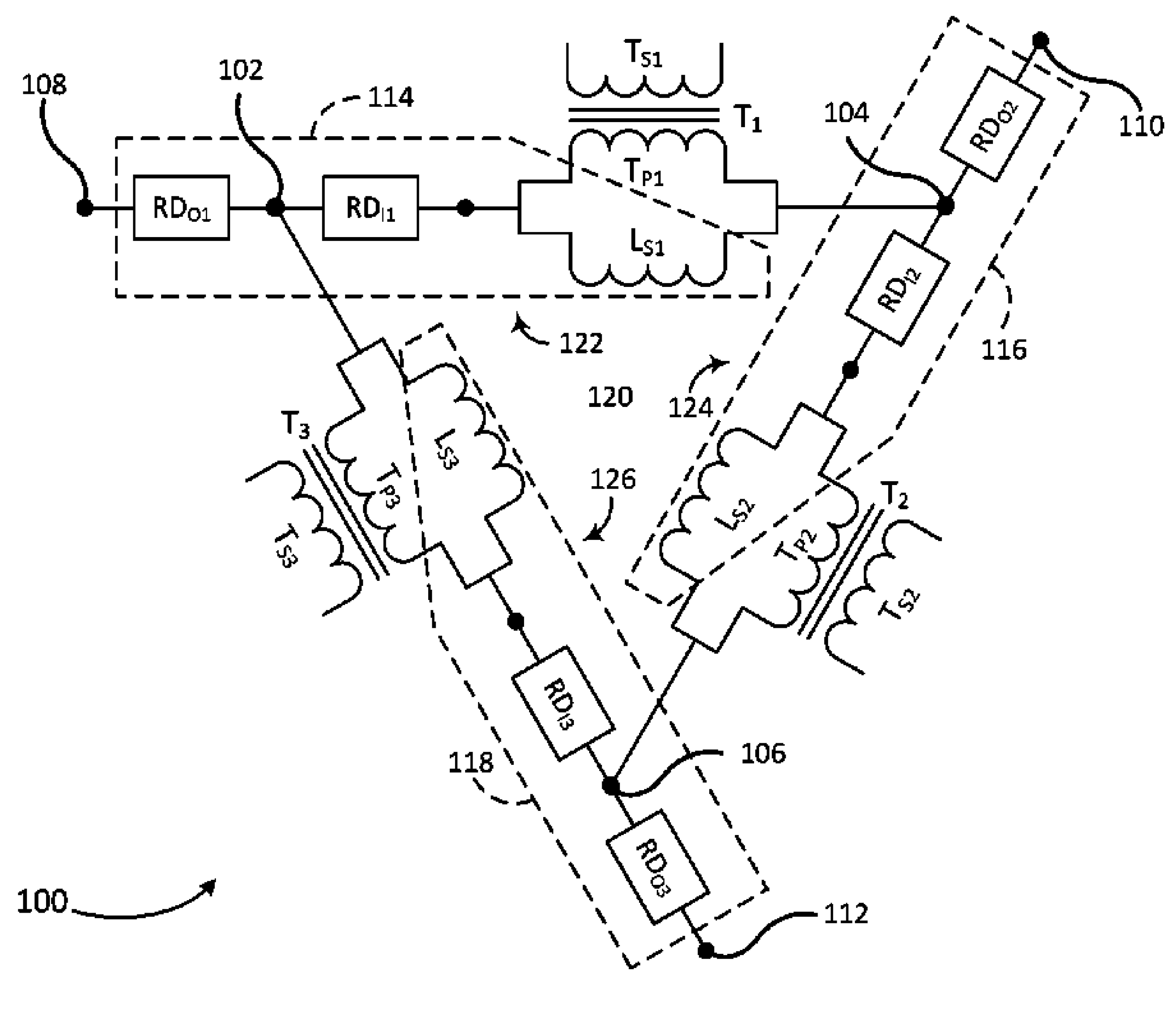
(57) **ABSTRACT**

A resonant circuit includes first, second, and third input nodes configured to receive a three phase input power and is formed as a delta circuit including a first leg connected between a first corner node and a second corner node, a second leg connected between the second corner node and a third corner node, and a third leg connected between the third corner node and the first corner node. A first outer resonant device is connected between the first input node and the first corner node, a second outer resonant device connected between the second input node and the second corner node, and a third outer resonant device connected between the third input node and the third corner node. Each leg of the delta circuit includes an inner resonant device connected in series with a corresponding transformer.

14 Claims, 12 Drawing Sheets



(51) **Int. Cl.**

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H02M 1/08	(2006.01)
H02M 1/00	(2006.01)
H02M 7/48	(2007.01)

(52) **U.S. Cl.**
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(58) **Field of Classification Search**
CPC .. H02M 2001/0074; H02M 2007/4815; Y02B 70/1433; Y02B 70/1491; Y02B 70/1441
See application file for complete search history.

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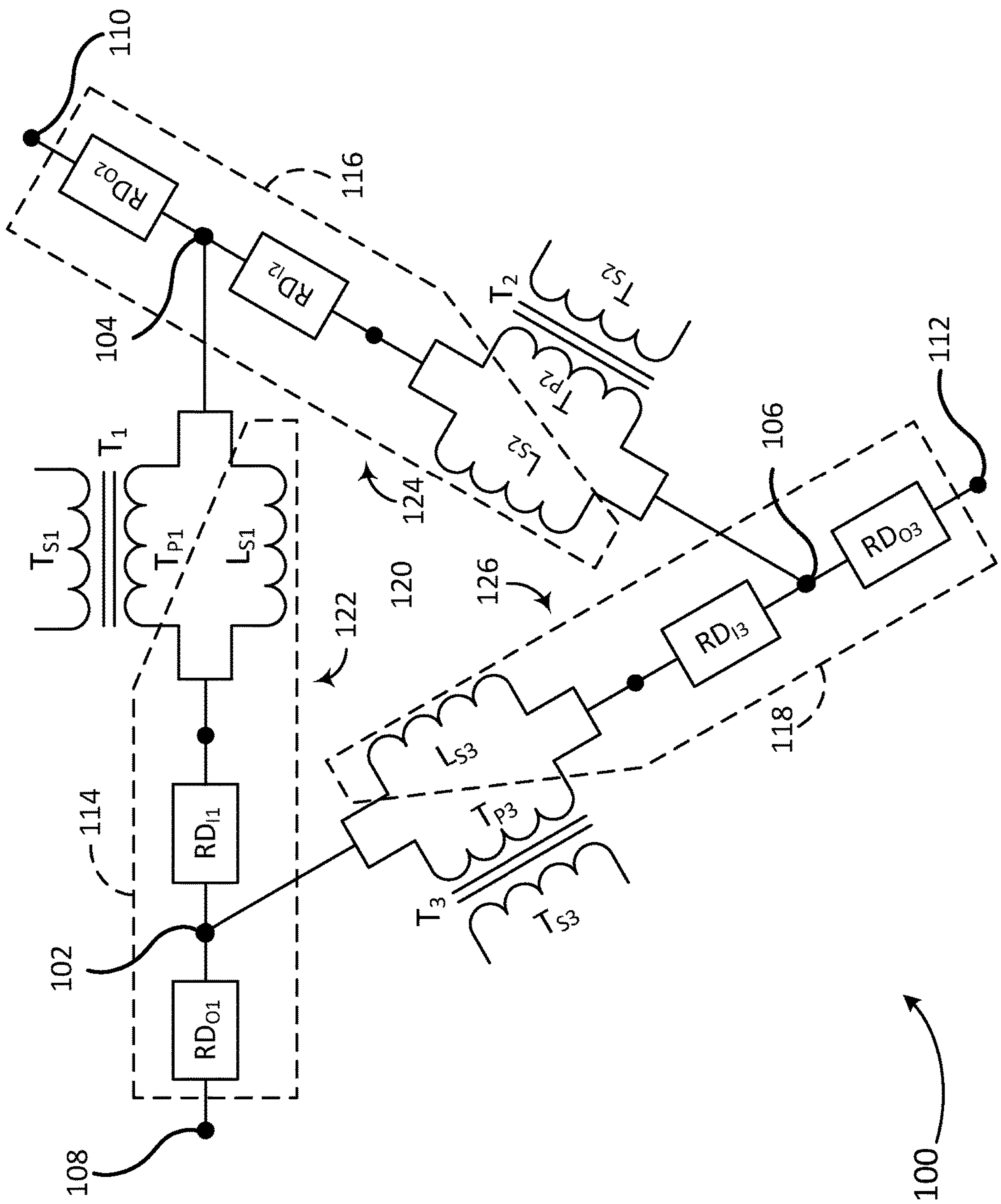
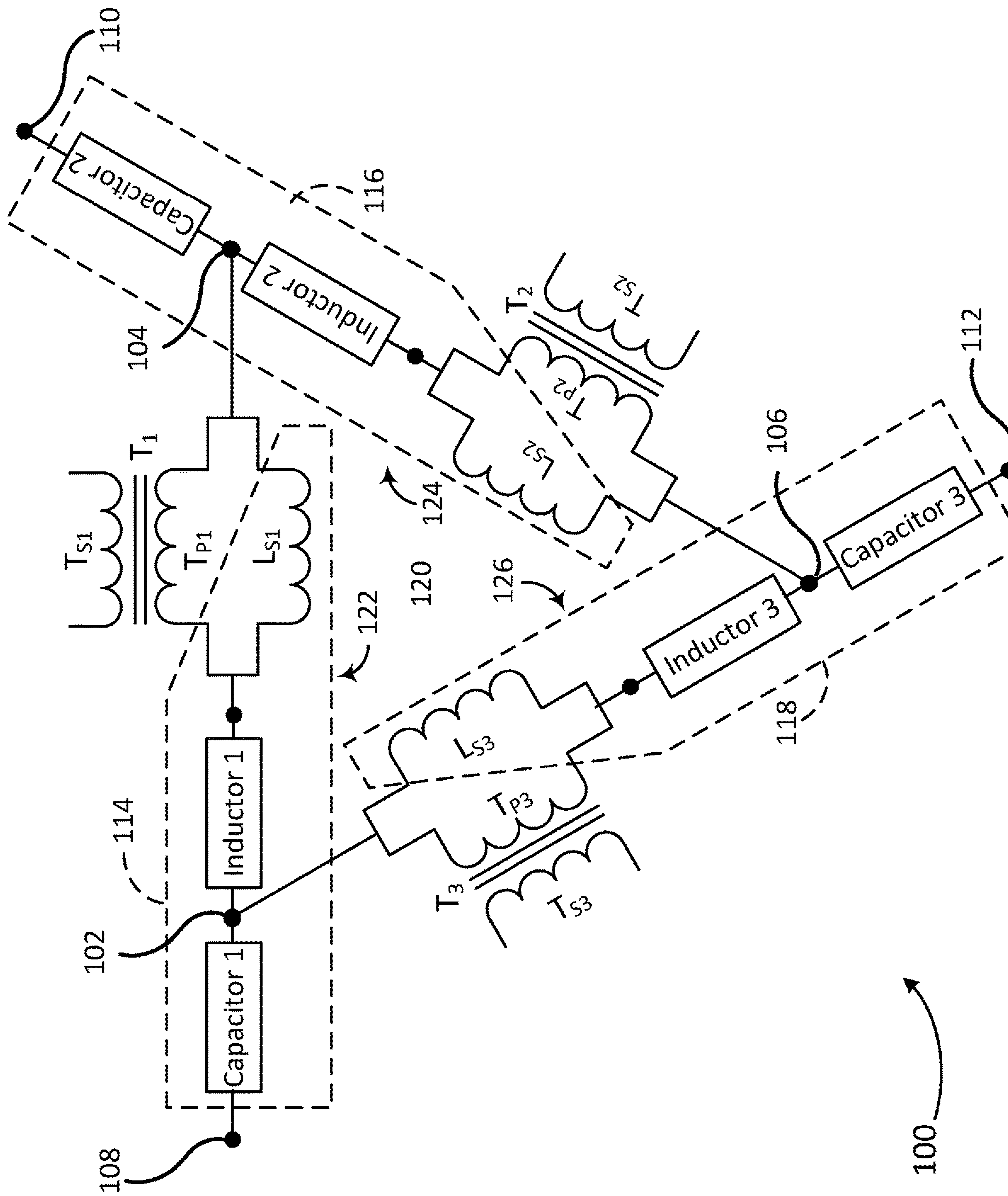

110
RD_{O2}
116
104
RD_{I2}
T_2
T_{S2}
T_{P2}
L_{S2}
106
112
RD_{O3}
RD_{I3}
124
126
118
T_1
T_{S1}
T_{P1}
L_{S1}
122
120
L_{S3}
T_{P3}
T_3
T_{S3}
114
RD_{I1}
102
RD_{O1}
108
100

Figure 1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Inductor 2
116
104
T_2
T_{S2}
T_{P2}
L_{S2}
112
106
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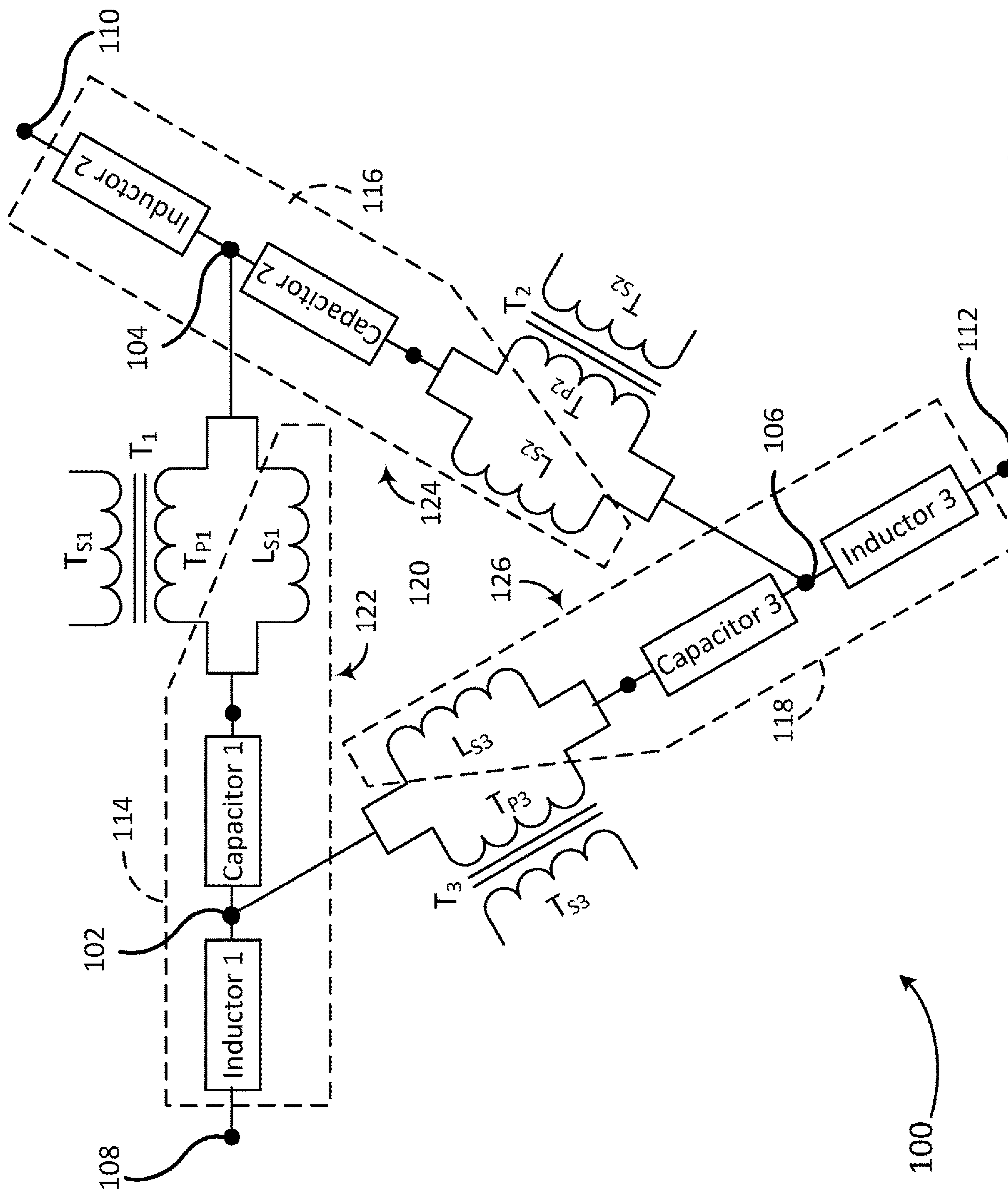
Inductor 3
T_1
T_{S1}
T_{P1}
L_{S1}
124
120
126
122
118
L_{S3}
T_{P3}
T_3
T_{S3}
Inductor 1
114
102
Capacitor 1
108
100

Figure 1a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104
Capacitor 2
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TP2
LS2
124
106
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TP1
LS1
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Capacitor 3
122
118
LS3
Capacitor 1
114
TP3
T3
TS3
102
Inductor 1
108
100

Figure 1b

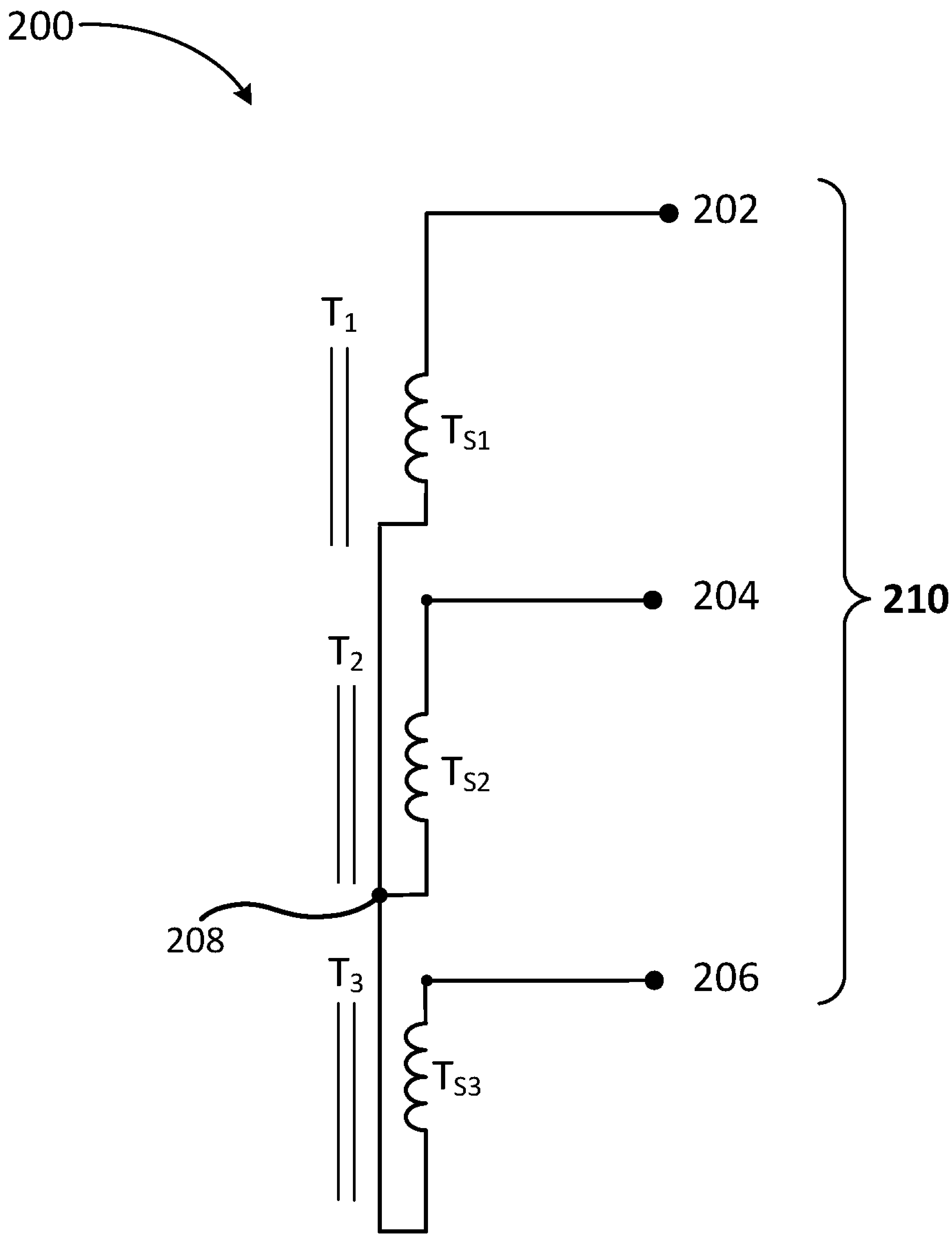


Figure 2

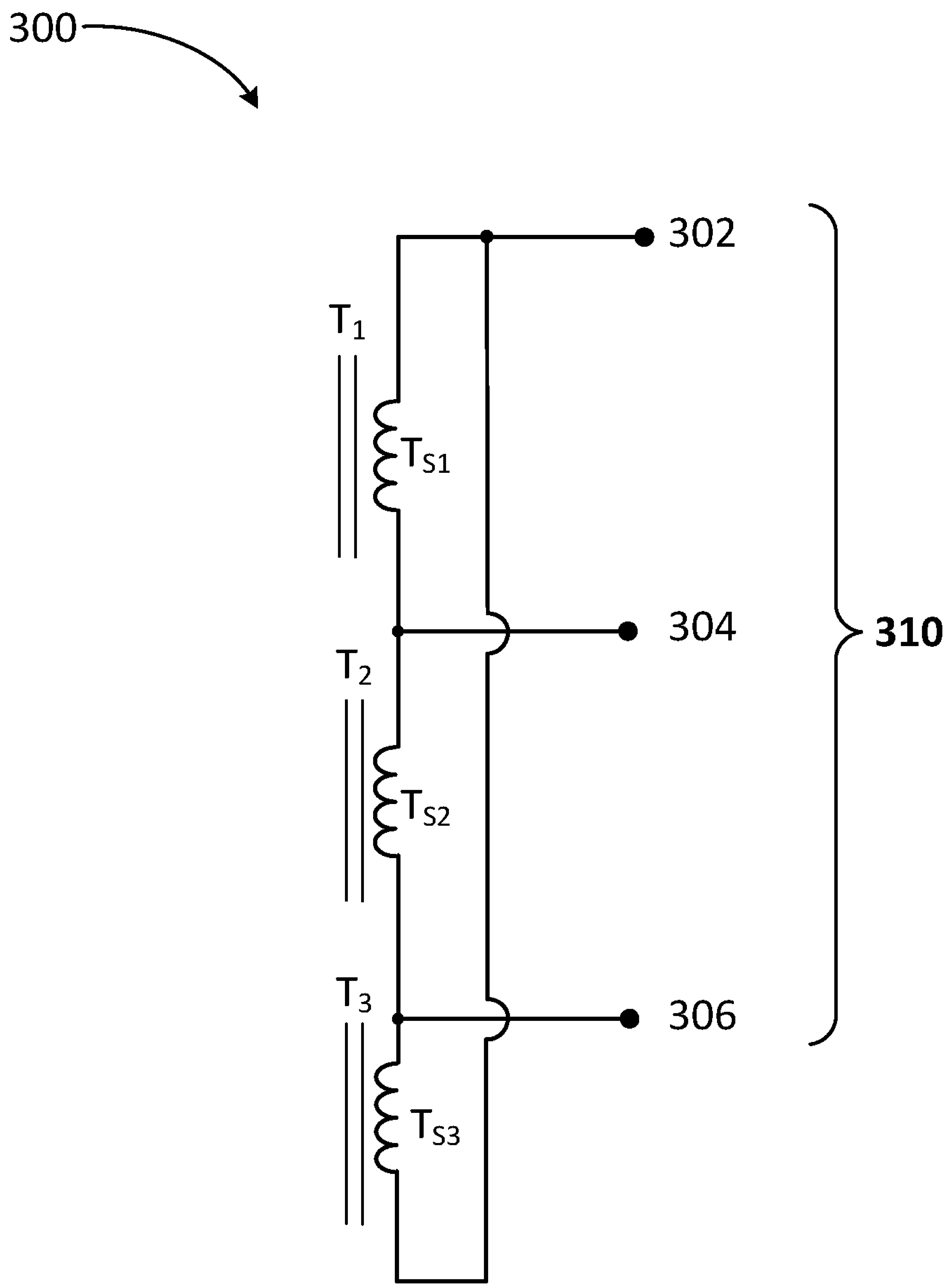
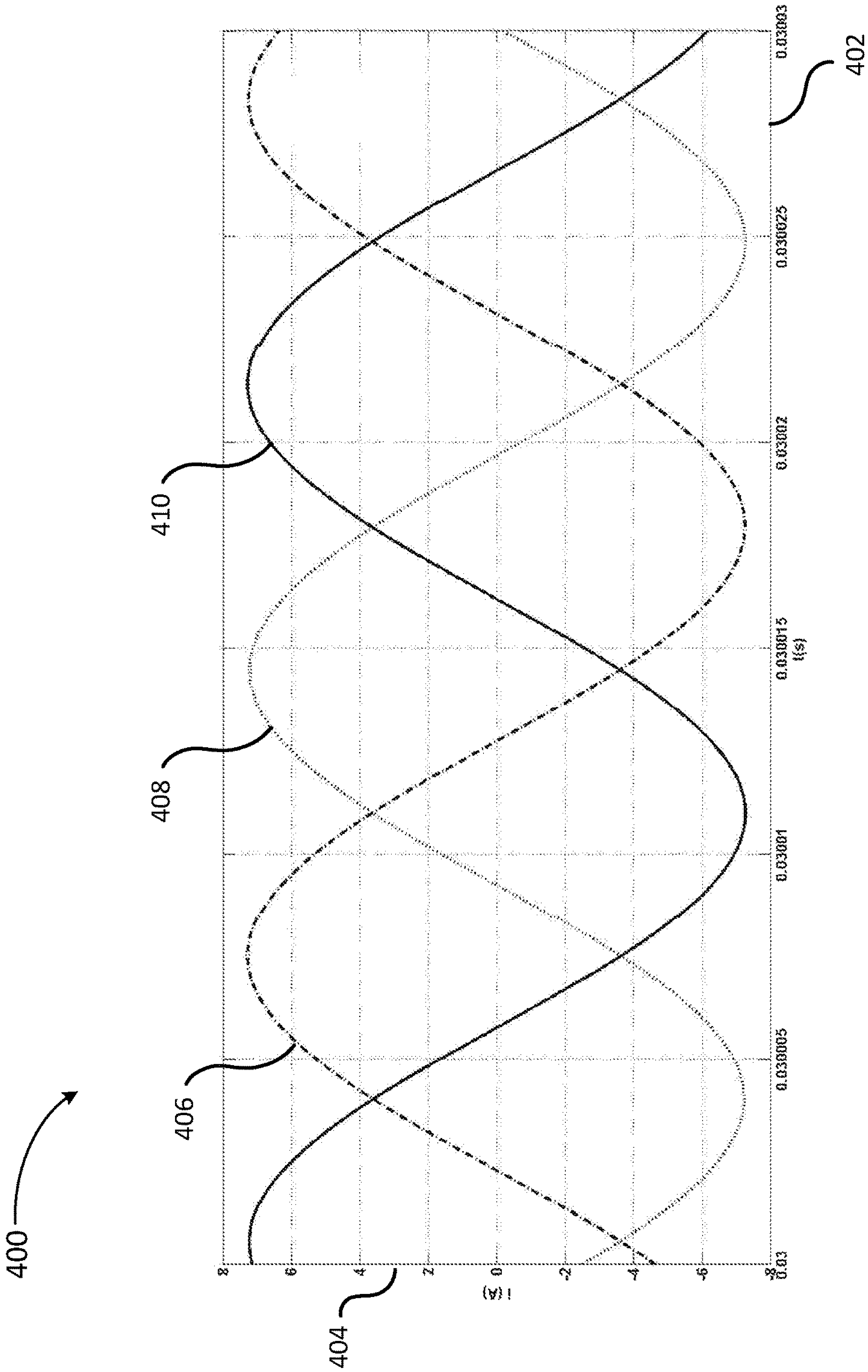


Figure 3


400
402
404
406
408
410
i (A)
t(s)
8
6
4
2
0
-2
-4
-6
-8
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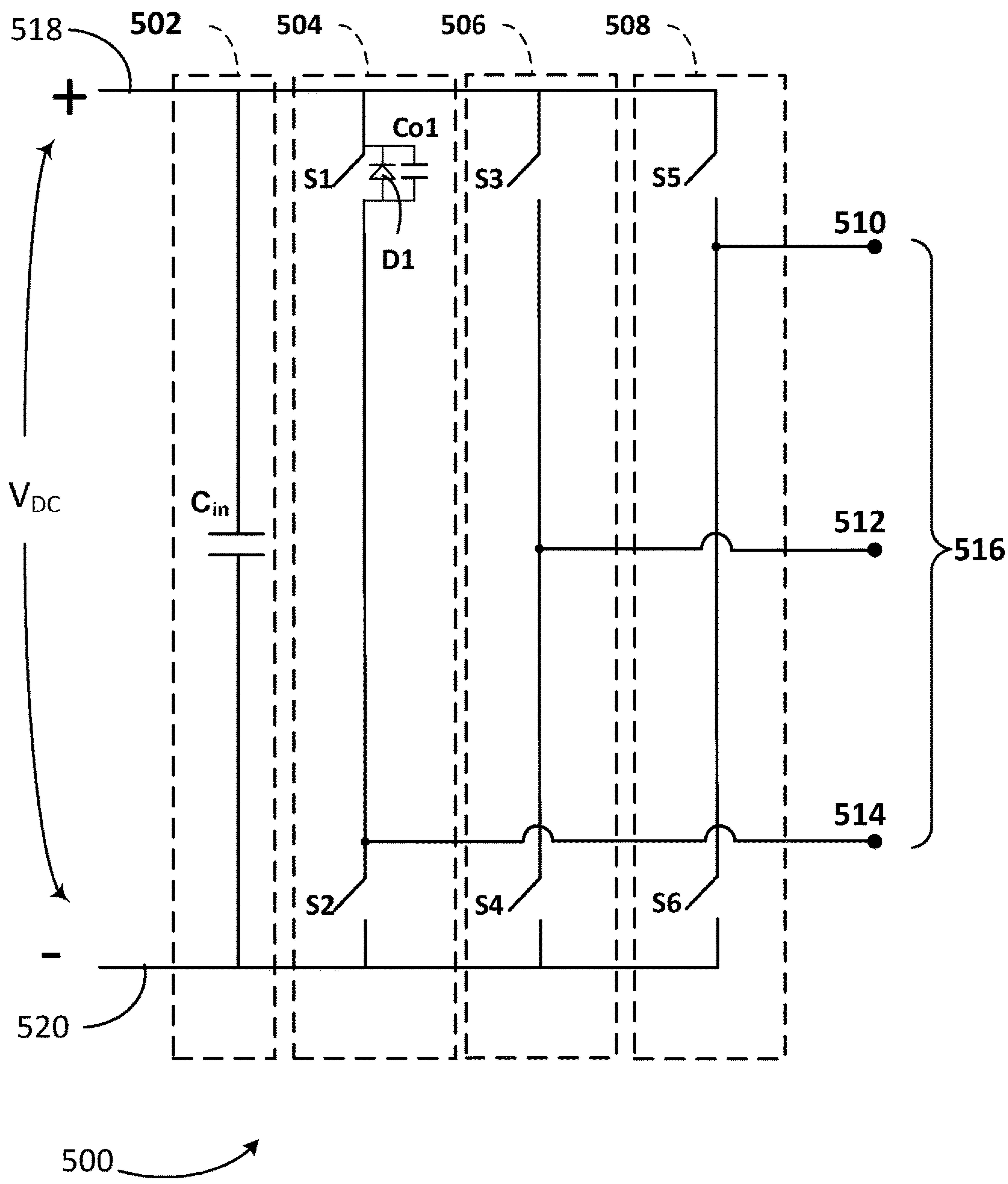
0.030005
0.03001
0.030015
0.03002
0.030025
0.03003

Figure 4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506
508
+
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S1
S3
S5
D1
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C_{in}
512
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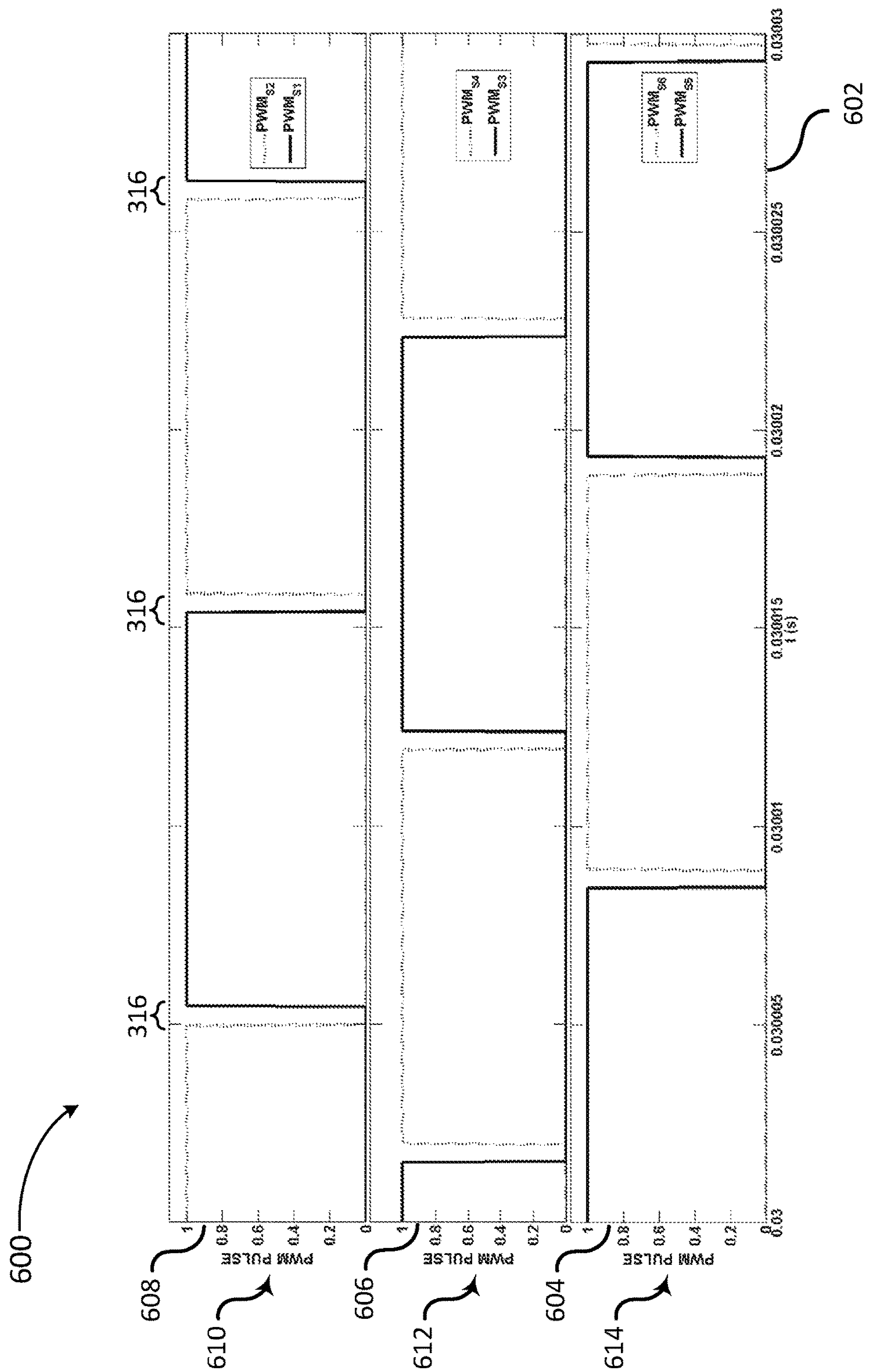
S4
S6
-
520
500

Figure 5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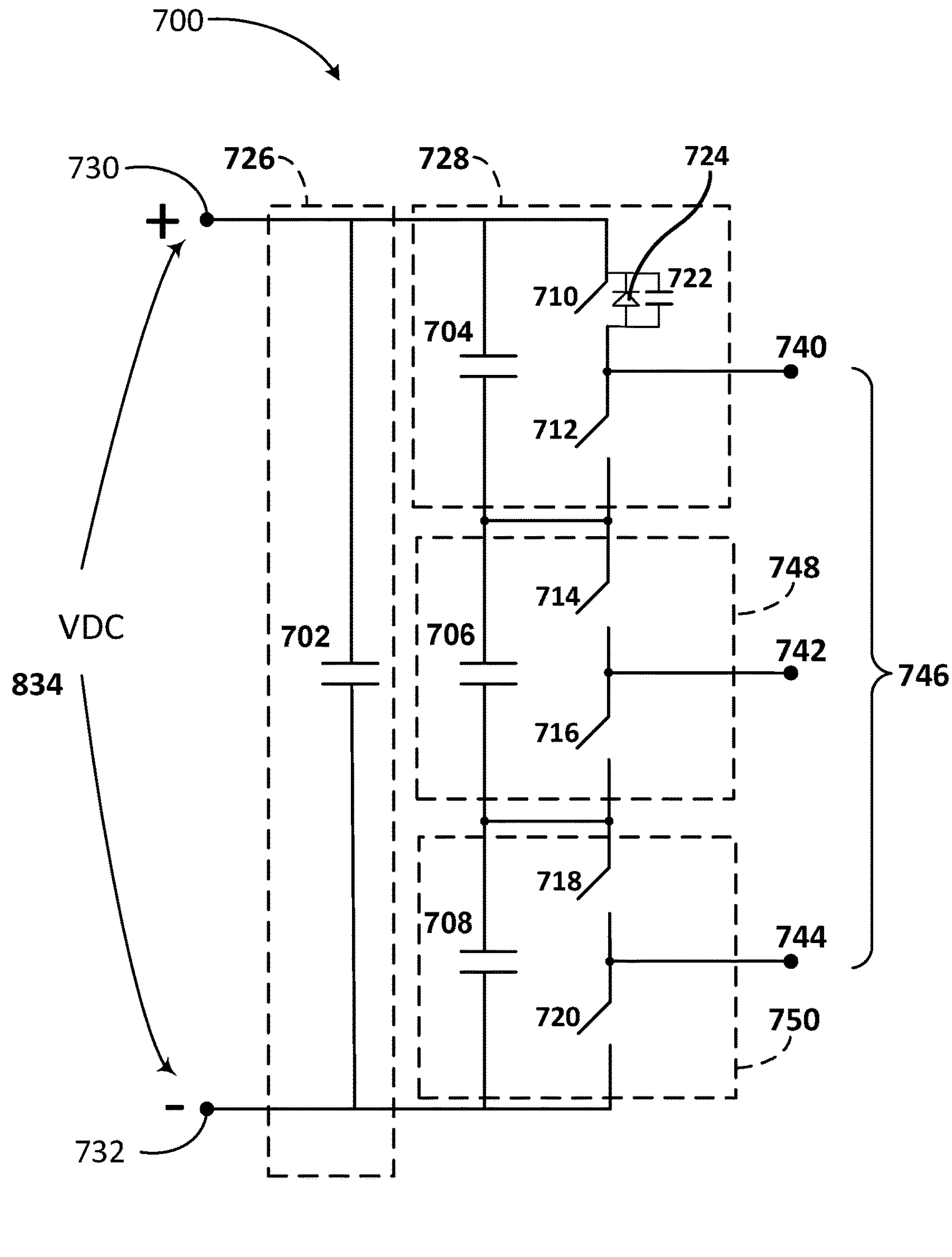
602
604
606
608
610
612
614
316
316
316
PWM PULSE
PWM PULSE
PWM PULSE
PWM_{S2}
PWM_{S1}
PWM_{S4}
PWM_{S3}
PWM_{S6}
PWM_{S5}
1
0.8
0.6
0.4
0.2
0
0.03
0.030005
0.03001
0.030015
t (s)
0.03002
0.030025
0.03003

Figure 6



700
730
726
728
724
+
710
722
704
740
712
748
714
VDC
702
706
742
746
834
716
718
708
744
720
750
-
732

Figure 7

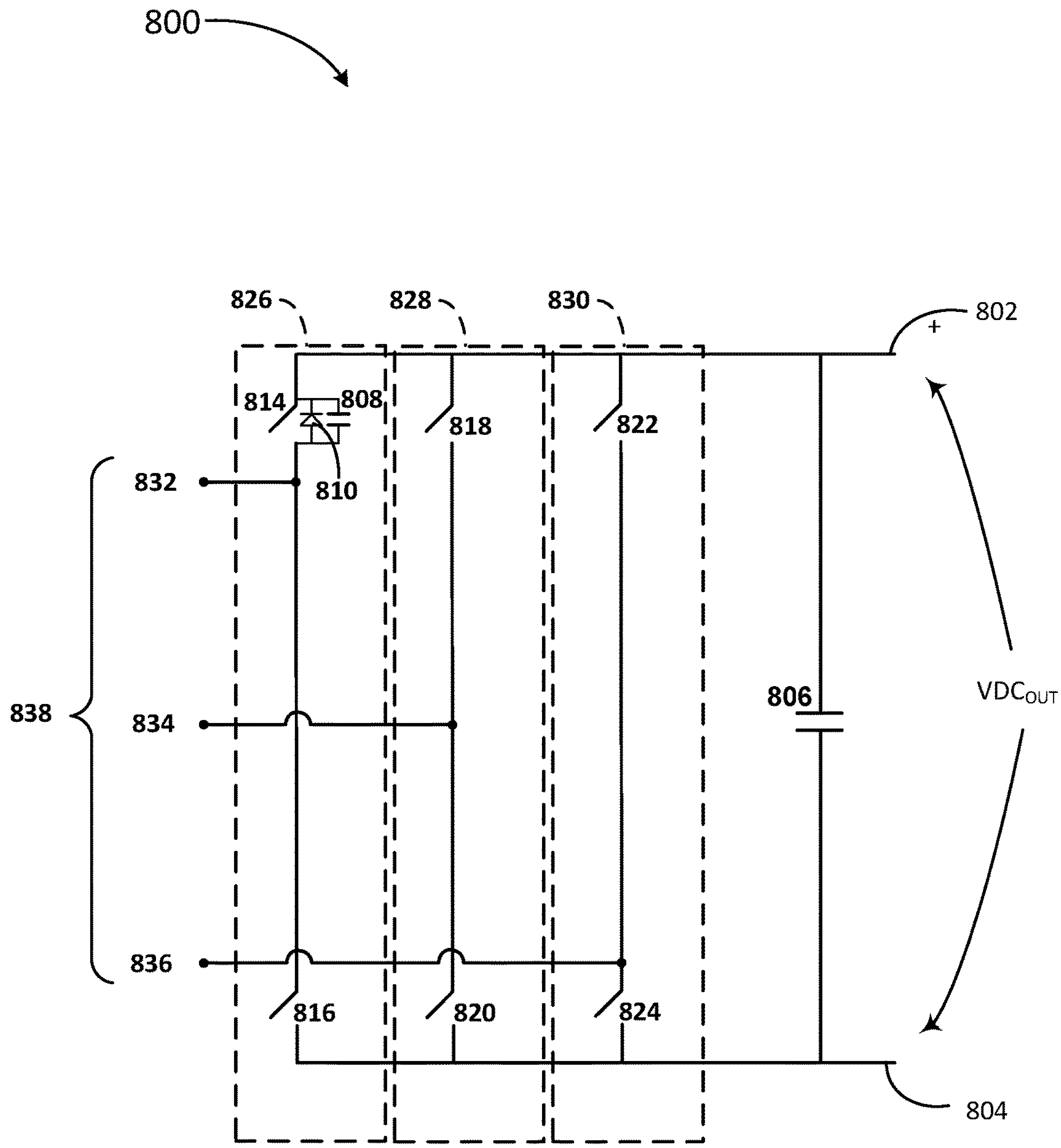

800
826
828
830
802
+
814
808
818
822
832
810
838
834
806
VDC$_{OUT}$
836
816
820
824
804

Figure 8

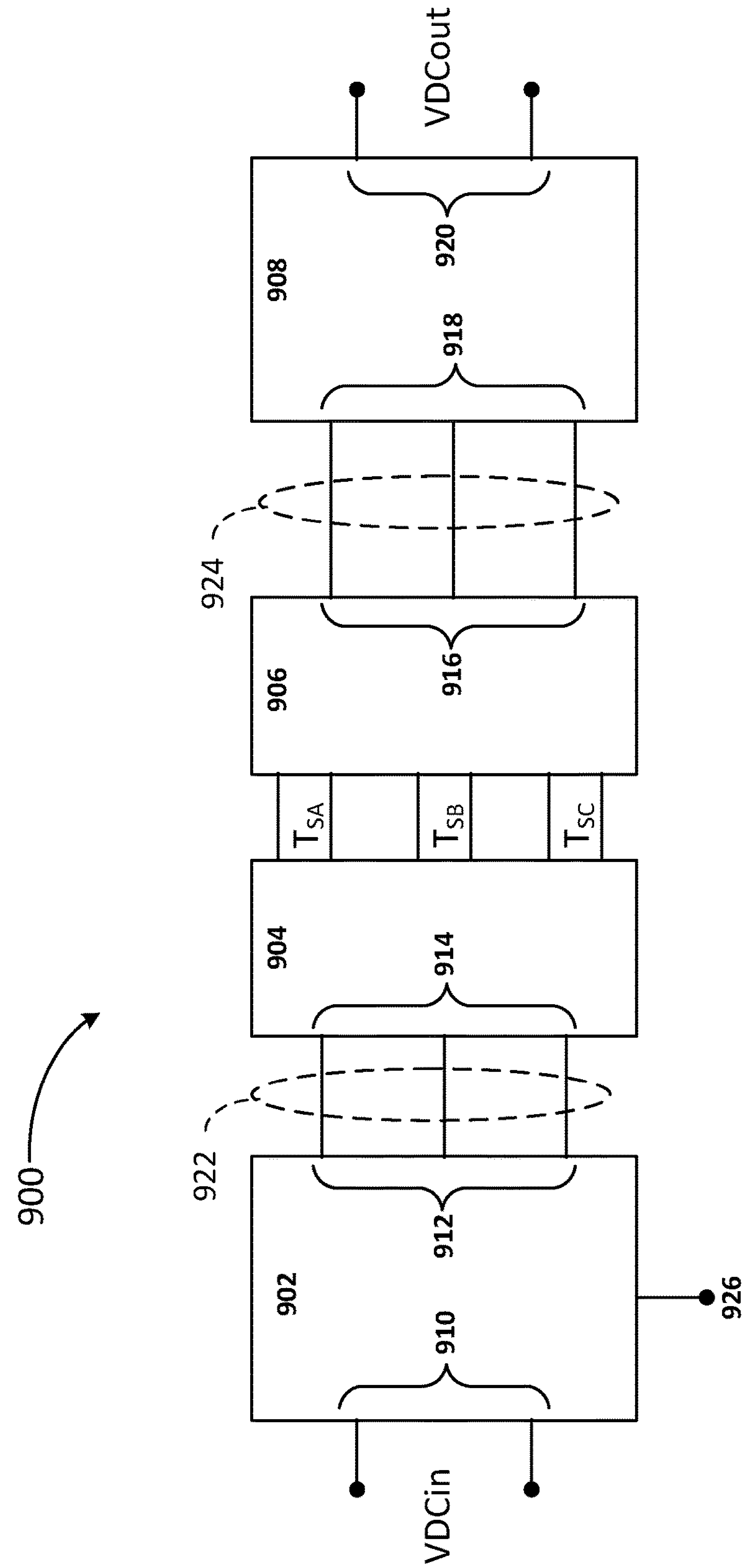
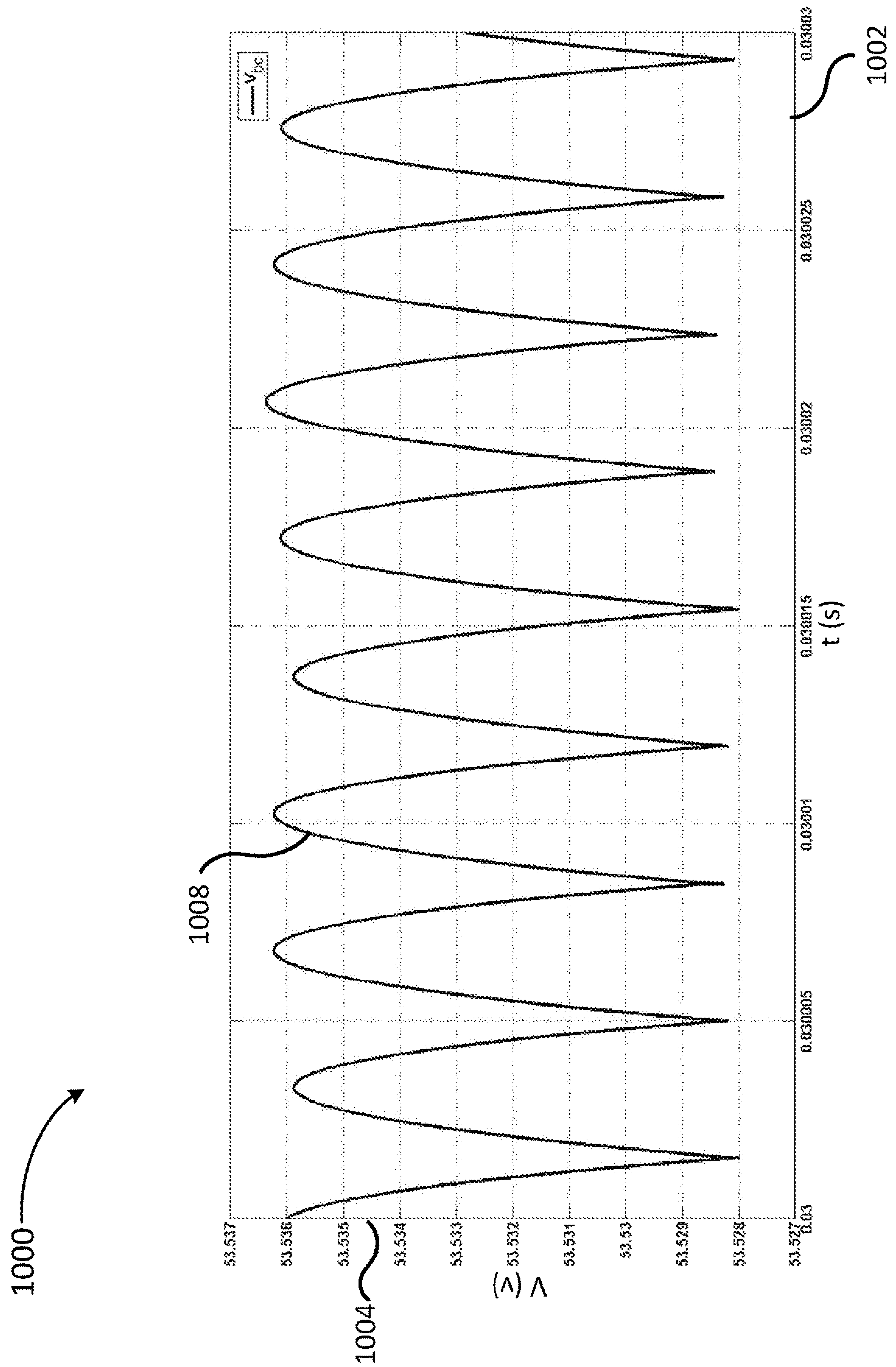

VDCout
908
920
918
924
906
916
TSA
TSB
TSC
904
914
900
922
902
912
910
926
VDCin

Figure 9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1002
1004
1008
V (V)
t (s)
v_{DC}
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53.536
53.535
53.534
53.533
53.532
53.531
53.53
53.529
53.528
53.527
0.03
0.030005
0.03001
0.030015
0.03002
0.030025
0.03003

Figure 10

RESONANT DC-DC CONVERTER

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of International Application No. PCT/EP2016/060876, filed on May 13, 2016, the disclosure of which is hereby incorporated by reference in its entirety.

TECHNICAL FIELD

The aspects of the present disclosure relate generally to power conversion apparatuses and more particularly to resonant DC to DC power converters.

BACKGROUND

Resonant DC to DC converters are considered by many to be attractive power conversion solutions for the many benefits they can provide. Following a resonant tank with transformers provides galvanic isolation which is important for level conversion as well as for safety. In certain applications, such as thin film solar panels, galvanic isolation is required for proper operation. Resonant converters also have inherent properties, such as soft switching of the semiconductor switches, which lead to high efficiency and low noise.

A commonly used type of resonant converter is known as the LLC resonant converter, named for the two inductors and one capacitor used to form its resonant tank. The LLC resonant converter has gained popularity due to its ability to achieve high efficiency. However, drawbacks of this type of converter include high AC currents in the output capacitors resulting in higher than desired power losses as well as the large volume or size taken up by the output filter components.

Combining or paralleling multiple LLC converters and interleaving their outputs with appropriate pulse width modulation (PWM) can reduce output ripple current and help reduce the volume required for the output filter capacitor. However due to voluntary and regulatory requirements, further improvements in efficiency and size are still desirable and may be required in certain applications. Thus, there is a need for improved resonant DC to DC converter topologies that can deliver better efficiency and low noise from smaller packages.

Accordingly, it would be desirable to provide a DC-DC converter topology that addresses at least some of the problems identified above.

SUMMARY

It is an object of the embodiments of the present invention to provide improved resonant DC to DC converter topologies that can deliver better efficiency and lower noise from smaller packages. This object is solved by the subject matter of the independent claims. Further advantageous modifications can be found in the dependent claims.

According to a first aspect of the embodiments of the present invention the above and further objects and advantages are obtained by a resonant circuit including a first input node, a second input node, and a third input node, where each of the first, second and third input nodes are configured to receive one phase of a three phase input power. The resonant circuit is formed as a delta circuit including a first leg connected between a first corner node and a second corner node, a second leg connected between the second

corner node and a third corner node, and a third leg connected between the third corner node and the first corner node. The resonant circuit also includes a first outer resonant device connected between the first input node and the first corner node, a second outer resonant device connected between the second input node and the second corner node, and a third outer resonant device connected between the third input node and the third corner node. Each leg of the delta circuit includes an inner resonant device connected in series with a corresponding transformer. Locating the inner resonant devices inside the delta circuit and the outer resonant devices outside the delta circuit improves the performance of the DC to DC converter, such as by improving the zero voltage switching performance.

In a first possible implementation form of the resonant circuit according to the first aspect the first leg includes a first inner resonant device connected in series between the first corner node and a first transformer, the second leg includes a second inner resonant device connected in series between the second corner node and a second transformer, and the third leg includes a third inner resonant device connected in series between the third corner node and a third transformer. Locating the inner resonant devices inside the delta circuit and the outer resonant devices outside the delta circuit improves the performance of the DC to DC converter.

In a second possible implementation form of the resonant circuit according to the first possible implementation form of the first aspect the first outer resonant device, the second outer resonant device, and the third outer resonant device, are capacitors, and the first inner resonant device, the second inner resonant device, and the third inner resonant device are inductors. This implementation form improves the zero voltage switching efficiency of an inverter circuit used to provide the three phase power to the resonant circuit.

In a third possible implementation form of the resonant circuit according to the first or second possible implementation forms of the first aspect as such the first outer resonant device, the second outer resonant device, and the third outer resonant device are inductors, and the first inner resonant device, the second inner resonant device, and the third inner resonant device are capacitors. This implementation form improves the zero voltage switching efficiency of an inverter circuit used to provide the three phase power to the resonant circuit.

In a fourth implementation form of the resonant circuit according to the first aspect as such or to the first through third implementation forms of the first aspect the first inner resonant device, the second inner resonant device, and the third inner resonant device are incorporated into a single integrated inductive device. This implementation form improves the power density of the resonant circuit.

In a fifth possible implementation form of the resonant circuit according to the first aspect as such or to the first through fourth implementation forms of the first aspect the first outer resonant device, the second outer resonant device and the third outer resonant device are incorporated into a single integrated inductive device. Integrating the three inductive devices into a single integrated inductive device increases the power density of the resonant circuit.

In a sixth possible implementation form of the resonant circuit according to the first aspect as such or to the first through fifth possible implementation forms the first transformer includes a first primary winding connected in parallel with a first shunt inductor, the second transformer includes a second primary winding connected in parallel with a second shunt inductor and the third transformer includes a third primary winding connected in parallel with a third shunt inductor. This implementation form provides better control over the shunt inductor.

In a seventh possible implementation form of the resonant circuit according to the first aspect as such or to the sixth possible implementation form of the first aspect the first shunt inductor, the second shunt inductor, and the third shunt inductor, are incorporated into a single integrated inductive device. Incorporating the three shunt inductors into a single inductive device reduces cost.

In an eighth possible implementation form of the resonant circuit according to the first aspect as such or to the sixth or seventh possible implementation forms of the first aspect the first shunt inductor, the second shunt inductor, and the third shunt inductor are formed by a magnetizing inductance of the first primary winding, the second primary winding, and the third primary winding respectively. This implementation form reduces the number of discrete electronic devices used to construct the resonant circuit.

In a ninth possible implementation form of the resonant circuit according to the first aspect as such or to the sixth through eighth possible implementation forms of the first aspect the first transformer includes a first secondary winding magnetically coupled to the first primary winding, the second transformer includes a second secondary winding magnetically coupled to the second primary winding, and the third transformer includes a third secondary winding magnetically coupled to the third primary winding, and wherein the first secondary winding, the second secondary winding, and the third secondary winding are connected together in a delta configuration. This implementation form allows three phase power to be output through only three conductors.

In a tenth possible implementation form of the resonant circuit according to the first aspect as such or to the ninth possible implementation form of the first aspect the first secondary winding, the second secondary winding, and the third secondary winding are connected together in a star configuration. This implementation form allows three phase power to be output through only three conductors.

In an eleventh possible implementation form of the resonant circuit according to the first aspect as such or to the ninth or tenth possible implementation forms of the first aspect a first resonant circuit output node is connected to the first secondary winding, a second resonant circuit output node is connected to the second secondary winding, a third resonant circuit output node is connected to the third secondary winding, and a rectifier circuit is configured to receive a three phase AC power from the first resonant circuit output node, the second resonant circuit output node and the third resonant circuit output node to produce a DC power. This implementation form produces a DC power from the resonant circuit three phase AC output power.

In a twelfth possible implementation form of the resonant circuit according to the first aspect as such or to the first through eleventh possible implementation form of the first aspect an inverter circuit is configured to receive a DC input voltage, wherein the inverter circuit includes: a first half bridge circuit, a second half bridge circuit, and a third half bridge circuit, each connected in parallel across the DC input voltage and configured to provide a square wave voltage to a respective one of the first input node, the second input node and the third input node.

In a thirteenth possible implementation form of the resonant circuit according to the first aspect as such or to the twelfth possible implementation form of the first aspect the first half bridge circuit, the second half bridge circuit, and the third half bridge circuit are connected in series across the DC input voltage. This implementation form allows the resonant circuit to be driven from a DC power source.

In a fourteenth possible implementation form of the first aspect as such or to the first through thirteenth possible implementation forms of the first aspect the first transformer, the second transformer, and the third transformer are incorporated into a single integrated transformer device. Integrating all three transformer devices into a single integrated transformer device increases the power density and reduces manufacturing cost of the resonant circuit.

These and other aspects, implementation forms, and advantages of the exemplary embodiments will become apparent from the embodiments described herein considered in conjunction with the accompanying drawings. It is to be understood, however, that the description and drawings are designed solely for purposes of illustration and not as a definition of the limits of the disclosed invention, for which reference should be made to the appended claims. Additional aspects and advantages of disclosure will be set forth in the description that follows, and in part will be obvious from the description, or may be learned by practice of disclosure. Moreover, the aspects and advantages of disclosure may be realized and obtained by means of the instrumentalities and combinations particularly pointed out in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

In the following detailed portion of the present disclosure, disclosure will be explained in more detail with reference to the example embodiments shown in the drawings, in which:

FIG. **1** illustrates an exemplary three phase resonant circuit topology incorporating aspects of the disclosed embodiments.

FIG. **1***a* illustrates another exemplary three phase resonant circuit topology incorporating aspects of the disclosed embodiments.

FIG. **1***b* illustrates still another exemplary three phase resonant circuit topology incorporating aspects of the disclosed embodiments.

FIG. **2** illustrates a schematic diagram of an exemplary star configuration for the secondary windings of a three phase resonant circuit incorporating aspects of the disclosed embodiments.

FIG. **3** illustrates a schematic diagram of an exemplary delta configuration for the secondary windings of a three phase resonant circuit incorporating aspects of the disclosed embodiments.

FIG. **4** illustrates a graph showing current through resonant inductors of a resonant circuit incorporating aspects of the disclosed embodiments.

FIG. **5** illustrates a three phase inverter circuit for a resonant circuit incorporating aspects of the disclosed embodiments.

FIG. **6** illustrates a graph showing exemplary switch control signals for a resonant circuit incorporating aspects of the disclosed embodiments.

FIG. **7** illustrates a schematic diagram of an exemplary inverter circuit for a resonant circuit incorporating aspect of the disclosed embodiments.

FIG. **8** illustrates an exemplary embodiment of a three phase rectifier circuit for a resonant circuit incorporating aspects of the disclosed embodiments.

FIG. **9** illustrates a block diagram of an exemplary resonant DC to DC converter with a resonant circuit incorporating aspects of the disclosed embodiments.

FIG. **10** illustrates a graph showing a DC output voltage of an exemplary DC to DC converter based on a resonant circuit incorporating aspect of the disclosed embodiments.

DETAILED DESCRIPTION OF THE DISCLOSED EMBODIMENTS

Referring to FIG. **1** there can be seen an exemplary embodiment of a three phase resonant circuit **100** appropriate for use in a three phase resonant DC to DC converter. Three phase power as used herein refers to a type of electric power where three conductors, or phases, are used to carry an alternating current (AC), where each phase has the same frequency and voltage relative to a common reference and each phase is offset by 120 degrees from the other two phases. Generally, all phases in a three phase electric power have symmetric waveforms, such as a sinusoid or square wave, such that at any given time two of the phases will offset the third phase. The resonant circuit **100** is configured to receive a three phase electric power on three resonant circuit input nodes **108**, **110**, **112**, where each resonant circuit input node **108**, **100**, **112** is configured to receive a different one of the input phases.

Each resonant circuit input node **108**, **110**, **112** is coupled to a different corner node **102**, **104**, **106** of a three phase delta circuit **120** through an outer resonant device RD_{O1}, RD_{O2}, RD_{O3} as illustrated in FIG. **1**. The three outer resonant devices RD_{O1}, Rd_{O2}, RD_{O3} are energy storage type electronic elements located outside the delta circuit **120**. The term "resonant device" as used herein generally refers to an electronic component configured to store electric energy, such as an inductor or a capacitor. For example in one exemplary embodiment all three outer resonant devices RD_{O1}, RD_{O2}, RD_{O3} are capacitors. Alternatively, all three outer resonant devices RD_{O1}, RD_{O2}, RD_{O3} may be inductors.

A delta circuit as used herein is a conventional three phase circuit having three corner nodes and three circuit legs where each leg connects two of the corner nodes. In the example of FIG. **1** the circuit leg **122** connects corner node **102** to the corner node **104**, circuit leg **124** connects the corner node **104** to corner node **106** and the circuit leg **126** connects the corner node **106** to the corner node **102**. For the purposes of the description herein, the corner nodes **102**, **104** and **106** will be referred to as the first corner node **102**, the second corner node **104** and the third corner node **106**, merely for ease of understanding. In the delta circuit **120**, the three circuit legs **122**, **124**, **126** are substantially the same, having the same configuration, type, and value of circuit elements.

As shown in FIG. **1**, delta circuit leg **122** has an inner resonant device RD_{I1} coupled in series with a transformer T_1. In the example of FIG. **1**, transformer T_1 includes primary winding T_{P1}. A shunt inductor L_{S1} is coupled in parallel with the transformer primary winding T_{P1}. Similarly, delta circuit legs **124** and **126** have an inner resonant device RD_{I2}, and RD_{I3}, respectively, coupled in series with a corresponding transformer T_2 and T_3, respectively. In the example of FIG. **1**, transformer T_2 includes primary winding T_{P2}, and transformer T_3 includes primary winding T_{P1}. Transformer T_2 also includes a shunt inductor L_{S2}, while transformer T_3 includes shunt inductor L_{S3} In the example of FIG. **1**, shunt inductors L_{S2} and L_{S3} are respectively coupled in parallel with the corresponding transformer primary winding T_{P2}, and T_{P3}.

Similar to the outer resonant devices RD_{O1}, RD_{O2}, RD_{O3} described above, the inner resonant devices RD_{I1}, RD_{I2}, RD_{I3}, all include similar types of energy storage element. In embodiments where the outer resonant devices RD_{O1}, RD_{O2}, RD_{O3} are capacitors, the inner resonant devices RD_{I1}, RD_{I2}, RD_{I3} may all be inductors. In embodiments where the outer resonant devices RD_{O1}, RD_{O2}, RD_{O3} are inductors, the inner resonant devices RD_{I1}, RD_{I2}, RD_{I3} may be capacitors.

A secondary winding T_{S1}, T_{S2}, T_{S3} is magnetically coupled to each primary winding T_{P1}, T_{P2}, T_{P3} respectively and provides galvanic isolation between the input power, which is applied to the resonant circuit input nodes **108**, **110**, **112**. An output power of the resonant circuit **100** is taken from the transformer secondary windings T_{S1}, T_{S2}, T_{S3}. In certain embodiments it is desirable to configure a turn ratio between the primary windings T_{P1}, T_{P2}, T_{P3} and the transformer secondary windings T_{S1}, T_{S2}, T_{S3}, thereby allowing easy configuration of a change in the output power level.

Each phase or leg **122**, **124**, **126** includes a resonant tank **114**, **116**, **118**, effectively coupled in series with the load, as it is reflected to the transformer primary winding T_{P1}, T_{P2}, T_{P1}. In operation the resonant tank **114**, **115**, **116** acts as a voltage divider allowing the power applied to the load to be regulated by changing impedance of the resonant tank **114**, **116**, **118**. Thus, the output power may be regulated by changing the frequency of the power received on the resonant circuit input nodes **108**, **110**, **112**.

In the exemplary resonant circuit **100**, each resonant tank **114**, **116**, **118** is split such that the shunt inductance L_{S1}, L_{S2}, L_{S3} and the inner resonant device RD_{I1}, RD_{I2}, RD_{I3} are located inside the delta circuit **120**. The outer, resonant device RD_{O1}, RD_{O2}, RD_{O3} in each resonant tank **114**, **116**, **118** is located outside the delta circuit **120**. In embodiments where the inner resonant device RD_{I1}, RD_{I2}, RD_{I3} is an inductor, the inner resonant devices RD_{I1}, RD_{I2}, RD_{I3} may be integrated with the main transformers T**1**, T**2**, and T**3**, thereby increasing the power density of the converter **100**. Alternatively, in embodiments where the inner resonant devices RD_{I1}, RD_{I2}, RD_{I3} are inductors, the three inductors may be integrated into a single inductive device.

The illustrated resonant circuit **100** topology also allows all three main transformers T**1**, T**2**, T**3** to be integrated into a single transformer. When the inner resonant devices RD_{I1}, RD_{I2}, RD_{I3} are inductors, these inductors may be integrated together into a single inductive device. The inner resonant inductors RD_{I1}, RD_{I2}, RD_{I3} may also be integrated along with the three main transformers T**1**, T**2**, T**3** to form a single transformer/inductive device.

FIG. **2** illustrates a schematic diagram of an exemplary three phase star configuration **200** appropriate for coupling the secondary windings T_{S1}, T_{S2}, T_{S3} of a three phase resonant circuit, such as the resonant circuit **100** described above. The three phase star configuration **200** is configured to produce a three phase AC output power **210** across three resonant circuit output nodes **202**, **204**, **206** which are coupled to the secondary windings T_{S1}, T_{S2}, T_{S3} of a resonant circuit **100**. A circuit node **208** is coupled to each of the secondary windings T_{S1}, T_{S2}, T_{S3} to form a virtual common node for the three phases of a three phase AC power **210**. The configuration **200** of the secondary or output windings T_{S1}, T_{S2}, T_{S3} is referred to as a star configuration, or a wye "Y" configuration. The star configuration **200** produces a three phase AC output power **210** at the resonant circuit output nodes **202**, **204**, **206** with the common node **208** acting as a virtual common.

Referring to FIG. **3**, in one embodiment the secondary windings T_{S1}, T_{S2}, T_{S3} of the resonant circuit **100** may be configured in a delta configuration **300**. In a delta configuration **300** the three secondary windings T_{S1}, T_{S2}, T_{S3} are coupled in series with each other, with the first secondary winding T_{S1} being coupled to the second secondary winding T_{S2}, the second secondary winding T_{S2} being coupled to the third secondary winding T_{S3}, and the third secondary winding T_{S3} being coupled back to the first secondary winding T_{S1}. The delta configuration **300** forms a triangular topology with a corner node between each pair of secondary windings. In the delta configuration **300** the three outputs **302**, **304**, **306** or corner nodes are formed between each pair of secondary windings T_{S1}, T_{S2}, T_{S3}. The delta configuration **300** produces a three phase AC power **310** at resonant circuit output nodes **302**, **304**, **306**.

FIG. **4** illustrates a graph **400** showing the currents **406**, **408**, **410** through the three resonant inductors of a resonant circuit, such as the exemplary resonant circuit **100** described above. The secondary transformer windings T_{S1}, T_{S2}, T_{S3} of the resonant circuit **100** may be coupled in either a star **200** or delta **300** configuration. The illustrated graph **400** measures time in seconds increasing to the right along a horizontal axis **402**, and measures current in amperes (A) increasing upward along a vertical axis **404**. The three inductor currents **406**, **408**, **410** are offset in phase by 120 degrees from each other thereby forming a three phase AC power.

As described above with reference to FIG. **1**, the resonant circuit **100** is configured to receive a variable frequency three phase AC input power at the resonant circuit input nodes **108**, **110**, **112**. Variable frequency three phase AC power suitable for supplying the resonant circuit **100** may be generated from a DC power using an inverter circuit. FIG. **5** illustrates a three phase inverter circuit **500** configured to receive a DC power V_{DC} and create a three phase AC power **516** appropriate for driving the resonant circuit **100**. The inverter circuit **500** is configured to receive the DC input power V_{DC} across positive (+) and negative (−) input rails **518**, **520**. An input capacitor C_{IN} is coupled across the input rails **518**, **520** and provides filtering of the DC input power V_{DC}. Three half bridge circuits **504**, **506**, **508** are coupled in parallel across the DC input power V_{DC} and may be operated to produce a three phase power **516** at three output nodes **510**, **512**, **514**. Each half bridge circuit **504**, **506**, **508** includes a pair of switches, S**1**, S**2**, S**3**, S**4**, and S**5**, S**6** respectively. These pairs of switches allow the output node **510**, **512**, **514** to be alternately coupled to the positive input rail **518** or to the negative input rail **520** to create an AC power signal at the corresponding output node **510**, **512**, **514**.

Certain switching devices S**1**, such as metal-oxide-semiconductor field-effect-transistors, (MOSFET) include a body diode D**1** in parallel with the switching device S**1**. This diode D**1** is necessary when zero voltage switching (ZVS) is implemented in the circuit, because the diode D**1** is conducting prior to the switch S**1** during turn-on. When a different type of switching device S**1** is used, such as an insulated gate bipolar transistor (IGBT), the switching device S**1** may not include an inherent diode D**1** and a separate diode D**1** needs to be added in parallel with the switching device S**1** as illustrated. MOSFET switching devices appropriate for use as the switches S**1**, S**2**, S**3**, S**4**, S**5**, S**6** in the inverter **500** include a parasitic capacitance that may be represented as a capacitor Co**1** in parallel with the switch S**1**. During operation this parasitic capacitance is discharged allowing the voltage across the switching device S**1** to go to substantially zero volts before the switch S**1** is turned on. This is referred to as zero voltage switching. There will be a capacitance, either parasitic capacitance inherent in the switching devices or as added capacitors, in parallel with the switch in all embodiments where ZVS is implemented. When MOSFET switching devices are used the capacitance Co**1** is inherent in the device and when IGBT switching devices are used a separate parallel capacitance Co**1** is added. As an aid to readability only the capacitance Co**1** and the diode D**1** associated with the switch S**1** are illustrated in the schematic diagram of FIG. **5**, however those skilled in the art will recognize that the remaining switches S**2**, S**3**, S**4**, S**5**, and S**6** also include similar parallel diodes and capacitances. The parallel diode D**1** and capacitance Co**1** are utilized during the ZVS function of the converter and are included in all converter topologies when ZVS is implemented. Any suitable type of switching device may be used for the switches S**1**, S**2**, S**3**, S**4**, S**5**, S**6** such as IGBT and MOSFET devices constructed from a variety of materials including silicon (Si), silicon-carbide (SiC), gallium nitride (GaN) as well as other semiconductor materials. By appropriately operating the switches S**1**, S**2**, S**3**, S**4**, S**5**, S**6**, the three half bridge circuits **504**, **506**, **508** can produce a three phase AC power at the inverter circuit **500** output nodes **510**, **512**, **514**. Each switch S**1**, S**2**, S**3**, S**4**, S**5** and S**6** is configured to be operated, i.e. turned on or off, by a switch control signal (not shown). FIG. **6** illustrates a graph showing exemplary switch control signals **600**, also referred to herein as pulse width modulated (PWM) signals, that may be used to operate the switches S**1**, S**2**, S**3**, S**4**, S**5** and S**6** to produce a three phase power suitable for driving the resonant circuit **100** described above. The exemplary graph of switch control signals **600** measures time increasing to the right along a horizontal axis **602**, and control signal magnitude (PWM PULSE) increasing upwards along each vertical axes **604**, **606**, **608**, where a switch control signal magnitude of one (1) represents a switch that is on or conducting current, and a control signal magnitude of zero (0) represents a switch that is off or is not conducting current.

The top graph **610** represents the control signals PWM_{S1}, PWM_{S2} for the upper switch S**1** and lower switch S**2**, respectively, of the first half bridge **504** shown in FIG. **5**. The middle graph **612** represents the control signals PWM_{S3}, PWM_{S4} for the upper switch S**3** and lower switch S**4**, respectively. of the second half bridge **506**. The bottom graph **614** represents the control signals PWM_{S5}, PWM_{S6} for the upper switch S**5** and lower switch S**6** of the third half bridge **606**, respectively.

Applying the switch control signals **600** to the switches S**1**, S**2**, S**3**, S**4**, S**5** and S**6** of the inverter **500** will generate a three phase AC output power **516** at the output nodes **510**, **512**, **514** of the inverter **500**. Note that during each switching period **616**, one switch in a half bridge circuit is turned off before the other switch is turned on. Because the switches S**1**, S**2**, S**3**, S**4**, S**5**, S**6** take a finite amount of time to turn OFF or ON, this switching period **616**, where both switch control signals for a half bridge are at zero magnitude or off, is used to allow the voltage across the capacitor Co**1** enough time to discharge prior to turning on the switch in order to achieve ZVS.

Referring again to FIG. **1**, splitting the resonant tank **114**, **116**, **118** such that the shunt inductance L_{S1}, L_{S2}, L_{S3} and the inner resonant device RD_{I1}, RD_{I2}, RD_{I3} are located inside the delta circuit **120** and the third resonant device RD_{O1}, RD_{O2}, RD_{O3} of each resonant tank **114**, **116**, **118** is located outside the delta circuit **120**, significantly improves the zero voltage switching (ZVS) performance of the inverter circuit, such as the three phase inverter circuit **500**, being used to drive the resonant circuit **100**. The improved ZVS performance results from the way the parasitic capacitance of the inner resonant device RD_{I1}, RD_{I2}, RD_{I3}, in embodiments where the inner resonant device RD_{I1}, RD_{I2}, RD_{I3} is an inductor, is treated. In these embodiments, the parasitic capacitance of the inner resonant device RD_{I1}, RD_{I2}, RD_{I3} is in series with the capacitance Co**1** over the switches S**1**, S**2**, S**3**, S**4**, S**5** and S**6**. By placing the inner resonant device RD_{I1}, RD_{I2}, RD_{I3} inside the delta circuit **120** the parasitic capacitance is significantly increased thereby reducing the energy needed for ZVS. This allows the resonant converter circuit configuration **100** to reduce the circulating ZVS current and, as a result, the total losses of a converter built around the resonant circuit **100** are also reduced.

FIG. **7** illustrates a schematic diagram of an inverter circuit **700** configured to convert a DC input voltage VDC to a three phase AC power **746** suitable for driving the resonant circuit **100**. The inverter circuit **700** is configured to receive a DC input power VDC across positive (+) and negative (−) input rails **730**, **732**. An input capacitor **702** is coupled across the input rails **730**, **732** and provides filtering of the DC input power VDC. In contrast with the inverter circuit **500** described above, the three half bridge converters **728**, **748**, **750** of the inverter circuit **700** are coupled in series across the input power VDC. The three half bridge circuits **728**, **748**, **750** may be operated to produce a three phase AC power **746** at three output nodes **740**, **742**, **744**.

Each half bridge circuit **728**, **748**, **750** shown in FIG. **7** includes a pair of switches **710**, **712**, **714**, **716**, and **718**, **720**, respectively. By alternately opening and closing the upper switches **710**, **714**, **718** and lower switches **712**, **716**, **720** in each half bridge circuit **728**, **748**, and **750** an AC square wave power signal can be created at the corresponding output node **740**, **742**, **744**, respectively. Operating the three half bridge circuits **728**, **748**, **750** with the switch control signals **600** described above results in a three phase AC power signal **746** on the output nodes **740**, **742**, **744** of the inverter **700**.

FIG. **8** illustrates an exemplary embodiment of a three phase rectifier circuit **800** configured to receive a three phase AC power **838** and produce a DC output power VDC_{OUT}. The exemplary rectifier circuit **800** receives a three phase AC power at the three rectifier circuit input nodes **832**, **834**, **836**. Three phase AC input power **838** may be produced for example by a resonant circuit, such as the three phase AC power **210** or **310** produced by the resonant circuit **100**, coupled to either the star circuit **200** or delta circuit **300**, respectively. The rectifier circuit **800** includes a positive (+) output rail **802** and a negative (−) output rail **804** for the DC output power VDC_{OUT}. An output filter capacitor **806** is coupled across the positive (+) and negative (−) output rails **802**, **804** and configured to filter noise and reduce ripple from the output power VDC_{OUT}. Three half bridge circuits **826**, **828**, **830** are coupled in parallel across the output rails **802**, **804**. Each half bridge circuit **826**, **828**, **830** is configured to receive one phase **832**, **834**, **836**, of a three phase AC power **838** at a center node **832**, **834**, **838** of each half bridge circuit **826**, **828**, **830** respectively. Each half bridge circuit **832**, **834**, **838** uses a pair of switches **814**, **816**, **818**, **820**, and **822**, **824**, respectively to rectify the three phase AC input power **838**. The switches **814**, **816**, **818**, **820**, **822**, **824** may be any appropriate type of switching device configured to conduct, or not conduct, electric current based on switch control signals, such as the switch control signals **600** described above.

As described above when the switching devices **814**, **816**, **818**, **820**, **822**, **824** are MOSFET type switches, each switch will include a body diode **810** and a parasitic capacitance **808** in parallel with the switch **814**. Alternatively, the switches may be implemented as IGBT or other suitable switching devices in which case the parallel diode **810** and capacitor **808** are added as separate electronic components. As before for clarity of illustration only the parallel diode **810** and capacitor **808** associated with switch **814** are shown, however those skilled in the art will recognize that the other switching devices **816**, **818**, **820**, **822**, **824** also have a diode and capacitor coupled in parallel with each switch **816**, **818**, **820**, **822**, **824**. In certain embodiments it may be beneficial to replace the switches **814**, **816**, **818**, **820**, **822**, **824** along with the parallel diode **810** and capacitance **808** with a simple diode rather than the transistor type switch **814**, **816**, **818**, **820**, **822**, **824** illustrated in FIG. **8**.

FIG. **9** illustrates an exemplary embodiment of a resonant DC to DC converter **900** configured to receive a DC input power VDCin and produce a regulated DC output power VDCout. The resonant DC to DC converter **900** includes an inverter **902**, which may include either of the inverter circuits **500** or **700** described above. The inverter **902** is configured to receive a DC input voltage VDCin across a pair of input nodes or connections **910** and produce a three phase AC input power **922** on a set of output nodes or connections **912**. A resonant circuit **904** is coupled to the three phase AC input power **922** via a set of resonant circuit input nodes **914**. The resonant circuit **100** described above and with reference to FIG. **1** is suitable for use as the resonant circuit **904**. In this example, the resonant circuit input nodes **914** correspond to the three resonant circuit input nodes **108**, **110**, **112**. The secondary windings T_{SA}, T_{SB}, T_{SC} of the resonant circuit **904** are coupled in an output configuration **906** such as the star configuration **200** or delta configuration **300** described above and with respect to FIG. **2** and FIG. **3**. The output configuration produces a three phase AC output power **924** on a set of output nodes **916**. The three phase AC output power **924** is coupled to the input nodes **918** of a rectifier **908**. The rectifier circuit **800** described above and illustrated in FIG. **8** is appropriate for use in the rectifier **908**. The rectifier **908** produces a filtered low ripple DC output power VDCout across a pair of output nodes **920**.

In certain embodiments it is advantageous to regulate the DC output power VDCout at a desired level. As discussed above, the three phase AC output power **924** produced by the resonant circuit **904** may be adjusted by varying the frequency of the three phase AC input power **922** being supplied to the resonant circuit input nodes **914**. To facilitate regulation of the output power VDCout, the inverter **902** may be configured to accept an input signal **926** that can vary the frequency of the three phase AC input power **922** produced by the inverter **902**. Thus, by varying the input signal **926** in accordance with fluctuations in the output power VDCout, the output power VDCout may be regulated at a desired set point.

FIG. **10** illustrates a graph **1000** showing an exemplary DC output voltage **1008** as may be produced by the exemplary resonant DC to DC converter **900**. The graph **1000** measures time in seconds increasing to the right along a horizontal axis **1002**, and measures voltage in in volts (v) increasing upward along a vertical axis **1004**. The DC output power **1008** has a nominal voltage of about 53.5 volts. Alternatively, the DC output power may be configured for any desired nominal voltage. As can be seen in the graph **1000**, the DC output power **1008** has relatively small ripple varying from about 53.528 volts and 53.536 volts or about 0.015%.

Thus, while there have been shown, described and pointed out, fundamental novel features of disclosure as applied to the exemplary embodiments thereof, it will be understood that various omissions, substitutions and changes in the form and details of devices and methods illustrated, and in their operation, may be made by those skilled in the art without departing from the spirit and scope of the presently disclosed invention. Further, it is expressly intended that all combinations of those elements, which perform substantially the same function in substantially the same way to achieve the same results, are within the scope of disclosure. Moreover, it should be recognized that structures and/or elements shown and/or described in connection with any disclosed form or embodiment of disclosure may be incorporated in any other disclosed or described or suggested form or embodiment as a general matter of design choice. It is the intention, therefore, to be limited only as indicated by the scope of the claims appended hereto.

What is claimed is:

1. A resonant DC-DC converter circuit comprising:

a first input node, a second input node, and a third input node, each of the first, second and third input nodes configured to receive one phase of a three phase input power;

a delta circuit comprising a first leg connected between a first corner node and a second corner node, a second leg connected between the second corner node and a third corner node, and a third leg connected between the third corner node and the first corner node; and

a first outer resonant device connected between the first input node and the first corner node; a second outer resonant device connected between the second input node and the second corner node; and a third outer resonant device connected between the third input node and the third corner node,

wherein the first leg consists of a first inner resonant device and a first transformer, the first inner resonant device is connected in series between the first corner node and the first transformer, the second leg consists of a second inner resonant device and a second transformer, the second inner resonant device is connected in series between the second corner node and the second transformer, and the third leg consists of a third inner resonant device and a third transformer, the third inner resonant device is connected in series between the third corner node and the third transformer.

2. The resonant DC-DC converter circuit of claim **1** wherein the first outer resonant device, the second outer resonant device, and the third outer resonant device each comprises a capacitor, and the first inner resonant device, the second inner resonant device, and the third inner resonant device each comprises an inductor.

3. The resonant DC-DC converter circuit of claim **1**, wherein the first outer resonant device, the second outer resonant device, and the third outer resonant device each comprises an inductor, and the first inner resonant device, the second inner resonant device, and the third inner resonant device each comprises a capacitor.

4. The resonant DC-DC converter circuit of claim **1**, wherein the first inner resonant device, the second inner resonant device, and the third inner resonant device are incorporated into a single integrated inductive device.

5. The resonant DC-DC converter circuit of claim **1** wherein the first outer resonant device, the second outer resonant device, and the third outer resonant device are incorporated into a single integrated inductive device.

6. The resonant DC-DC converter circuit of claim **1** wherein the first transformer comprises a first primary winding connected in parallel with a first shunt inductor, the second transformer comprises a second primary winding connected in parallel with a second shunt inductor and the third transformer comprises a third primary winding connected in parallel with a third shunt inductor.

7. The resonant DC-DC converter circuit of claim **6** wherein the first shunt inductor, the second shunt inductor, and the third shunt inductor are incorporated into a single integrated inductive device.

8. The resonant DC-DC converter circuit of claim **6**, wherein the first shunt inductor, the second shunt inductor, and the third shunt inductor each comprises a magnetizing inductance of the first primary winding, the second primary winding, and the third primary winding respectively.

9. The resonant DC-DC converter circuit of claim **6** wherein the first transformer comprises a first secondary winding magnetically coupled to the first primary winding, the second transformer comprises a second secondary winding magnetically coupled to the second primary winding, and the third transformer comprises a third secondary winding magnetically coupled to the third primary winding, and wherein the first secondary winding, the second secondary winding, and the third secondary winding are connected together in a delta configuration.

10. The resonant DC-DC converter circuit of claim **6** wherein the first secondary winding, the second secondary winding, and the third secondary winding are connected together in a star configuration.

11. The resonant DC-DC converter circuit of claim **9** comprising a first resonant circuit output node connected to the first secondary winding, a second resonant circuit output node connected to the second secondary winding, and a third resonant circuit output node connected to the third secondary winding; and a rectifier circuit configured to receive a three phase AC power from the first resonant circuit output node, the second resonant circuit output node and the third resonant circuit output node to produce a DC power.

12. The resonant DC-DC converter circuit of claim **1** comprising an inverter circuit configured to receive a DC input voltage, wherein the inverter circuit comprises:

a first half bridge circuit, a second half bridge circuit, and a third half bridge circuit, each connected in parallel across the DC input voltage and configured to provide a square wave voltage to a respective one of the first input node, the second input node and the third input node.

13. The resonant DC-DC converter circuit of claim comprising an inverter circuit configured to receive a DC input voltage, wherein the inverter circuit comprises: wherein a first half bridge circuit, a second half bridge circuit, and a third half bridge circuit are connected in series across the DC input voltage and configured to provide a square wave voltage to a respective one of the first input node, the second input node and the third input node.

14. The resonant DC-DC converter circuit of claim **1** wherein the first transformer, the second transformer, and the third transformer are incorporated into a single integrated transformer device.

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